AGUSTÍN DE BETANCOURT Y MOLINA (1758–1824)

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Abstract. Agustín de Betancourt, together with José María de Lanz, is known as co-author of "Essai sur la composition des machines", considered to be the first modern treatise on machines and the first book that contains a proposal for the classification of mechanisms based on criteria of transformation of motion. Two periods can be distinguished in his biographical trajectory: the first one is in Spain at the service of the Spanish Crown, from his birth in 1758 until 1808, and the second one is in Russia at the service of the Russian Empire from 1808 until his death in 1824. This paper is focused on the works and contributions developed in the Spanish period.

Biographical Notes

Agustín José Pedro del Carmen Domingo de Candelaria de Betancourt y Molina was born on the 1st of February, 1758 in Puerto de la Cruz (Canary Islands, Spain), in the bosom of an enlightened family.

Fig. 1. A portrait of Agustín de Betancourt.

M. Ceccarelli (ed.), Distinguished Figures in Mechanism and Machine Science, 31–60.

His primary education was carried out in the Dominican Monastery of La Orotava. Agustín de Betancourt himself will say later that, from all he had learned throughout his life, nothing was as useful as the development during his first years in the Canary Islands of some textile machines, such as the thread covering machine, which were made as a hobby and had been the origin of his attraction to the mechanical arts.

In his biography, several periods can be distinguished: from 1778 to 1784 there is a first formative period in Madrid; from 1785 to 1791 there is a second formative period in Paris in which the future Royal Laboratory of Machines was developed; from 1792 to 1793 there is a period in Madrid as Director of the Royal Laboratory of Machines; from 1793 to 1796 he visited England where he had the opportunity to learn about Watt's works on the steam machine; from 1797 to 1798 he visited Paris where he published two important essays on the steam engine; for the period 1799 to 1807 he returned to Spain and created the School of Civil Engineering; for the period 1807 to 1808 he returned to Paris and published "Essai sur la composition des machines"; in 1808 he moved to Russia, remaining there until his death in 1824. Next, each one of these periods will be analyzed with greater detail.

Under a grant of the Secretary of Industry, D. José Gálvez, Betancourt moved to Madrid in October of 1778. From 1778 to 1784 he studied in Madrid at the Reales Estudios de San Isidro, directed by his cousin Estanislao Lugo-Viña Molina, where he learned Arithmetic, Algebra, Geometry, Trigonometry, Mathematical Analysis, Theory of Curved Lines, Differential and Integral Calculus and Mechanics (static and dynamic) and at the Real Academia de Bellas Artes de San Fernando where he studied Physics and Drawing. In 1783, D. José Moñino, Count of Floridablanca, first Secretary of State, put him in charge of a visit to inspect the mines of Almadén, given his recognized expertise. Betancourt wrote three important Reports about this inspection.

In 1784 he received a grant from the Secretariat of the Indies to study underground architecture (mine engineering). Simultaneously he received an order to visit the Channel of Aragón for an inspection. In April, on the way to France, he elaborated a new Report, but until today it remains lost. In Paris he participated in the activity of the École des Ponts et Chaussées.

In 1785 he went back to Madrid. After an interview with the Secretary of State, D. José Moñino, Count of Floridablanca, he was asked to establish in Spain a new school, namely, the Escuela de Caminos y Canales (School

of Roads and Channels, today's School of Civil Engineering). However, the agreements for this assignment were: Betancourt and a selected group of grant holders were to enroll at the École des Ponts et Chaussées in Paris in order to obtain the degree of Hydraulic Engineer; in this school, and other similar institutions, they would acquire expertise and mechanical specialization; and they were to collect models of machines of general utility in public works and industry.

On September 10, 1785, Betancourt went again to Paris, where he was well accepted from the Director of the School Jean Rodolphe Perronet and professor Gaspard François de Prony. In April 1788 the Spanish ambassador, the Count of Fernán-Núñez, visited Betancourt's home and workshop and was very impressed with the many scale models, so that in his letter to the Secretary of State, dated 23 April, he proposed the creation of a Laboratory of Machines in Madrid. In 1791, due to the situation in France, the King of Spain, Carlos IV, decided that Betancourt should return to Spain, bringing with him his collection of drawings and scale models. The whole collection (including 42 drawings) was received in Spain between July and September. In April 1792 the Laboratory, located in the Palacio del Buen Retiro, was opened to the public. On the 14th of October, 1792, Betancourt was officially appointed Director of the Laboratory. The whole collection was composed of 270 models, 359 drawings and 99 reports.

Due to scarce interest shown in the Laboratory, evidenced by the low number of visitors and because most of them were either curious or unemployed people instead of people interested in applying the models to public works or to industry, he asked for permission to go abroad to study, first in England, from 1793 to 1796, and later to France, from 1797 to 1798.

In England he visited factories and saw different types of machines, which attracted, without a doubt, Betancourt's interest in research on the theory of machines. While in France, he submitted two important reports to the Académie des Sciences of Paris. In the first, "Mémoire sur une machine à vapeur à double effet", he revealed to the Continent the double-action steam engine, which he had observed in action in England between 1793 and 1796. This report led Jacque-Constantin Périer to construct the first double-action steam engine in France. In the second report, "Mémoire sur la force expansive de la vapeur de l'eau", he published the results of a series of measurements establishing the relation between temperature and steam pressure.

From 1797 to 1798, in Paris, he received a grant to improve the optical telegraph. In 1799 the Secretary of State, Don Mariano Luis de Urquijo, created the General Inspectorate of Roads and the Body of Engineers of Roads, which Betancourt joined with the category of Commissioner.

In 1799 he returned to Spain. From 1799 to 1800 he dedicated himself fundamentally to the tasks of installing a line of optical telegraphs between Madrid and Cádiz, building 70 turrets at intervals of ten to twelve kilometers. In 1802 Betancourt became the Chief Inspector, and from that position he founded the School of Roads and Channels, locating it in the Real Gabinete de Máquinas (Royal Laboratory of Machines). In that same year the basic textbooks for the education of the students were printed: "Geometría descriptiva" by Monge and "Tratado de Mecánica" by Francoeur. By that time, Lanz had joined the faculty of the Institution. From 1802 to 1807, Betancourt remained in charge of the School of Roads and Channels, the Royal Laboratory of Machines and the General Inspectorate of the Corps of Road Engineers. From 1802 to 1805 Lanz and Betancourt both taught in the classrooms of the School.

From May to October 1807, Lanz and Betancourt were together again in Paris. It was then when the work, developed previously by Lanz and Betancourt, was reconstructed, reviewed and presented in the Ecole Politecnique with the title of "Essai sur la composition des machines". In October 1808, due to the state of war created in Spain,[1] Betancourt left for Russia and worked for Czar Alexander I. In Russia he spent great efforts to successfully make new inroads for engineering through several activities in design, teaching, and organization. This activity was fully attributed to Betancourt and to this date he is remembered in the Russian history of Mechanical Engineering. In 1809 he organized the Institute of Engineers of Communication Routes in Russia, of which he was inspector and advisor. In 1816 he was President of the Committee of Constructions and Hydraulic Works and also of the newly created committee for the construction of the fair at Nizhni Nóvgorod. In

[1] His definitive departure from Spain to Russia was due to the difficult situation through which Spain passed after the Napoleonic invasion and to the warm welcome on the part of Czar Alexander I. In a letter addressed to his brother Jose in 1814, he commented on the matter: "Since I observed the enmity that reigned in Spain between the Prince of Asturias and Godoy, I supposed that a revolution should arise in Spain and that in such case it was necessary, in order not to perish with my family, to look for asylum in a foreign kingdom in which to put it out of danger, and it seemed to me that Russia would be the most appropriate".

1818 he was named Chief of a main directorate of the Department of Communication Routes. In Russia he improved the arms industry and constructed bridges using a new system of arches. He built, in collaboration with Carbonnier, the hall of the riding school of Moscow, which was by then the largest hall without inner supports; the span of its roof was said to be forty meters long. He also constructed the aqueduct of Taïtzy and set up a state paper industry. In 1822 he was removed from this position and saw his authority diminished. In 1824 Betancourt died in Saint Petersburg.

List of Main Works

Manuscripts

Catálogo de la colección de Modelos, Planos y Manuscritos que, de orden del Primer Secretario de Estado, ha recogido en Francia Don Agustín de Betancourt y Molina. 1792. (Catalog of the collection of Models, Plans and Manuscripts that, by order of the First Secretary of State, Don Agustín de Betancourt and Molina were collected in France.)

Descripción del establecimiento de Yndrid donde se funden y barrenan los cañones de hierro para la Marina Real de Francia. 1791. (Description of the factory at Yndrid where iron cannons are melted and drilled for the Royal Navy of France.)

Description d'une machine à couper les roseaux et les autres plantes aquatiques qui obstruent beaucoup de canaux et de rivières navigables. (Description of a machine to cut the water reeds and other plants which block many channels and navigable rivers.)

Dessin de la machine pour faire monter et descendre les bateaux d'un canal inférieur et réciproquement, sur deux plans inclinés, exécutée en Angleterre, dans le comté de Shropshire, sur le bord de la rivière de Severn, près du pont de fer à Coalbrookdale, à 4 lieus environ à l'ouest de Shefnal: Levé et dessiné sur les lieux par M. de Betancourt. (Drawing of a machine to lift and take down boats from a lower channel and reciprocally, on two inclined levels, carried out in England, in the county of Shropshire, on the river bank of Severn, close to the iron bridge of Coalbrookdale, 4 lieus approximately to the west of Shefnal: Surveyed and drawn on the spot by Mr. Betancourt.)

Explication des principales parties du moulin pour moudre le silex. 1796. (Explanation of the main parts of a mill to grind flint.)

Informe dirigido a Mariano Luis de Urquijo sobre el método de transmitir noticias a distancia por medio de señales inventado por José Fornell. 1799. (Report directed to Mariano Luis de Urquijo on a method for long-distance transmission of news by means of signals invented by Jose Fornell.)

Informe dirigido al Duque de Alcudia sobre la bomba hidráulica diseñada por Francisco Zacarías. 1793. (Report directed to the Duque of Alcudia on the hydraulic pump designed by Francisco Zacarías.)

Machine à curer proposée pour le port de Venise. (Cleaning machine proposed for the port of Venice.)

Mémoire sur une machine à vapeur à double effet. 1789. (Report on a double-acting engine.)

Memoria sobre la purificación del carbón de piedra, y modo de aprovechar las materias que contiene. 1785. (Report on the purification of stone coal, and the way to take advantage of the materials that it contains.)

Primera memoria sobre las aguas existentes en las Reales Minas de Almadén, en el mes de julio de 1783: y sobre las máquinas y demás concerniente a su extracción. 1783. (First report on the water found in the Royal Mines of Almadén, the month of July 1783: and on the machines and others affairs concerning its extraction.)

Segunda memoria sobre las máquinas que usan en las minas de Almadén, en que se expresan sus ventajas, y defectos, y algunos medios de remediarlos. 1783. (Second report on the machines used in the mines of Almadén, in which their advantages are expressed, and defects, and some means to remedy them.)

Tercera memoria sobre todas las operaciones que se hacen dentro del Cerco en que están los hornos de fundición de Almadén. 1783. (Third report on all the operations that are made in the surroundings of the smelting furnaces at Almadén.)

Printed

Mémoire sur la force expansive de la vapeur de l'eau, lu a l'Académie Royale des Sciences. 1790. (Report on the expansive force of steam, read at the Royal Academy of Sciences.)

Essai sur la composition des machines: Programme du cours élémentaire des machines pour l'an 1808 par M. Hachette. 1808. (Essay on the composition of machines: Program of the elementary course of machines for the year 1808 by Mr. Hachette.)

Essai sur la composition des machines. 2 éd, rev., corr. y augm. 1819. (Essay on the composition of machines. 2nd version reviewed, corrected and augmented.)

Analytical essay on the construction of machines: translated from French. 1820.

Versuch über die Zusammenstzung der Machinens: aus dem Französischen. 1829.

Essai sur la composition des machines. 3 éd, rev., corr. y augm. 1840. (Essay on the composition of machines: 3rd version reviewed, corrected and augmented.)

Review of Main Works on the Design of Mechanisms

There are two main works of Betancourt that are related to the Theory of Machines. The first one is "Essai sur la composition des machines" which was co-authored with José Maria de Lanz and was published in 1808, constituting the first modern treatise on machines in which a classification of mechanisms appears based on the transformation of motion. The second one is reflected in "Mémoire sur une machine à vapeur à double effet", presented to the Royal French Academy of Sciences in 1789, which contains a description of Watt's double-acting steam engine together with the development of a method of path-generating synthesis applied to dimensioning of Watt's mechanism.

The "Essai sur la composition des machines"

In 1808, as it has been already mentioned, the treatise written by Lanz and Betancourt was published. The title itself marked a substantial difference with respect to previous works: it deals with the composition of the machines, that is to say, it focuses the analysis not on the machine itself but on the mechanisms that constitute it.

The book comes accompanied by the first program of the Elementary Course of Machines, developed in l'École Polytechnique, that was given at that time by Jean Nicolas Pierre Hachette (1769–1834), disciple of Monge. In this program the initial steps that were taken in the creation of this first Course of Machines are reported. Monge proposed to dedicate two months of the first year of studies to the description of the elements of the machines and also to the machines used in public works, with which a new approach to

teaching on machines appears: the machines are combinations of elements, whose purpose is to transform motion.

In the *Journal of l'École*, Monge exposed his ideas:

> The forces of Nature at man's disposal have three different elements: mass, speed and direction of motion. Hardly ever do the three elements of the forces in question have the qualities that agree with the proposed target; and the main object of the machines is to turn the effective forces into others in which these elements are of such nature so as to produce the desired effect. Each machine is made-up of several elementary parts, each one with a particular target that can be reached in several different ways according to the circumstances. The enumeration of all the forms in which it is possible to change the elements of the forces and the description of the different means to produce the same change in different circumstances, must offer to the workers the greater resources for all classes of jobs.[2]

The program shows ten types of elemental transformations of motion:

Rectilinear continuous in:

1. Rectilinear continuous.
2. Rectilinear alternative.
3. Circular continuous.
4. Circular alternative.

Circular continuous in:

5. Rectilinear alternative.
6. Circular continuous.
7. Circular alternative.

Rectilinear alternative in:

8. Rectilinear alternative.
9. Circular alternative.

Circular alternative in:

10. Circular alternative.

[2] J.N.P. Hachette: "Sur le cours des machines de l'École Polytechnique", introduction to the 1808 edition of "Essai sur la composition des machines" of J.M. Lanz and A. Betancourt, p. VI.

The program contains an attached picture of elementary machines in which eighty nine mechanisms are classified according to the ten types of transformations of motion previously described.

The Council of Instruction of l'École, as recorded in the introduction of the Essai, affirmed with respect to the publication of the book:

> So it was the system according to which Mr. Hachette had begun the attached picture of the elementary machines, when he had knowledge that Mr. Lanz and Betancourt had elaborated a similar work in agreement with the same plan. The Council of Instruction, based on Mr. Monge and Hachette's report, proposed to the Governor that the result of Mr. Lanz and Betancourt's work (both commissioned by the Spanish government) should be put in print, the School paying for it. This work, transferred by its authors to the Polytechnic School, now appears under the title of "Essai sur la composition des machines". (The Council of Instruction of the School, which heard the reading of this article in its meeting of the 12th of August of 1808, has ordered to print it).[3]

The book served as support material to the Course of Machines. In the development of the text, the motion by means of a given curve is added together with the rectilinear and circular motion. This is a first important contribution because the two last motions predominated in the old machines. The curvilinear motion represents an advance in the possibilities of the machines.

The introductory commentary to the general table is very interesting because in it the authors explain the principles of classification and the utility of the table itself.

> Motions used in the mechanical arts are rectilinear, circular or are determined according to given curves; they can be continuous or alternative (backward and forward motion or swinging) and can consequently be combined in pairs resulting in fifteen different options or twenty one if each one of these motions is combined with another one of the same class. All machines have the aim of performing one or several of these twenty one combinations. This picture includes the exhibition of these different combinations of motions with all the

[3] J.N.P. Hachette (1808): "Sur le cours des machines de l'ÉŘcole Polytechnique", introduction to the 1808 version of "Essai sur la composition des machines" by J.M. Lanz and A. Betancourt, p. VIII.

> examples that we have been able to find; the examples will be represented aside, in greater size, adding the explanation and the uses to which each can be put. By means of this picture, great ease will be acquired in choosing and creating all classes of machines and in inventing new ones according to need.[4]

The combination of three trajectories (rectilinear, circular and curved) with two types of motion (continuous and alternative) gives rise to six combinations.

The combination of these six types of input motion with six types of output motion would give rise, theoretically, to thirty-six combinations, but they are reduced to twenty-one because some combinations do not appear.[5] In contrast to the ten combinations of Hachette's table twenty-one types of transformations appear. The general table contains one hundred and thirty-four mechanisms, as opposed to the eighty-nine of Hachette.

It is very important to emphasize the usefulness of the table and of the book given by the authors because of the novelty of its methodology, based on choosing mechanisms, to create and to invent new machines according to need.

With the purpose of helping in the identification of each one of these solutions, a classifying system was developed. Each figure is designated by a letter and a number that indicates its position in the table. In the same treatise the authors affirm that:

> Each horizontal row will be the object of a section designated with the same number; in it, the proposed target will be announced; the general solution of analogous problems to the transformation that needs to be carried out will be given; the particular cases or the different means of execution which we know will be developed, indicating the sources from where we have extracted this knowledge, and finally, thoughts

[4] Lanz (1808), illustration AK6.

[5] As for the circular continuous input there is no rectilinear continuous output; for the input according to a continuous curve there is no rectilinear continuous output nor circular continuous; for the rectilinear alternative input there is no rectilinear continuous output, circular continuous and by continuous curve; for circular alternative input there is neither rectilinear continuous nor rectilinear alternative output, there is no circular continuous and by continuous curve output; for the input according to an alternative curve there is only output according to an alternative curve. Altogether they make fifteen combinations that do not appear.

on the usefulness of these means and the diverse machines to which they have been applied will be added.[6]

The book contains a large classifying table in which all the mechanisms that are distributed according to the criteria of transformation of motion appear, such as it has been commented previously. Such mechanisms appear depicted on a greater scale throughout ten tables.

The tables come preceded by explanatory texts for each one of the mechanisms proposed. Sometimes, if the mechanisms are very elementary or very known, the explanation is concise; nevertheless, in most of the mechanisms, the authors explain their operation, they cite the sources from where they have obtained the data and they include the applications to which they have reference.[7]

As for the types of mechanisms, it can be indicated that the one hundred and thirty-four proposals contain mechanisms of all types: by frequency of appearance, gears predominate appearing thirty-nine times (wheels, racks, cylindrical, conical and worm crown gears), pulleys and cables appear thirty-three times; articulated mechanisms appear twenty-seven times; cams and escapements appear both eighteen times; worm gears appear six times; and chains appear five times. Seventeen mechanisms are operated by weights and eleven mechanisms are operated by springs.

Although the explanations might suggest that some of the solutions have been developed or improved by the authors, in two of them their applications are explicitly mentioned, and in another three, their design was made by Betancourt.[8] From these, mechanism I.17 seems to us especially interest-

[6] Lanz (1808), p. 2.

[7] As an example of the extensive research into sources, this commentary to the Archimedes' screw is included: "About the theory of Archimedes, Hydrodynamique by Daniel Bernouilli can be consulted; a Report by M. Pitot, printed in the Reports of l'Académie des Sciences in 1736; another one by Mr. Euler in the Reports of l'Académie imperial of Pétersbourg, volume V, year 1754; the work done by P. Belgrado, whose title is 'Theorie cochleae Archimedis, ab observationibus, experimentis et analyticis rationibus ducta', year 1767; the prize given in 1765 to M. Jean-Frédéric Hennert, by the Academy of Prusia; and the work done by M. Paucton, on the theory of the screw of Archimedes".

[8] Figure H1 corresponds to a wedge mechanism that is said that was used by Betancourt in England to raise the lower cylinder of a great rolling mill. In section S. II it is said that in "L'Architecture Hydraulique" by Prony, vol. II, there is the description of a procedure invented by Betancourt, to regulate the velocity of a steam engine by means of a floater provided with a siphon; in M7 an elevating water device, also attributed to Betancourt; in O8 a universal joint appears of which an application by Betancourt and Breguet

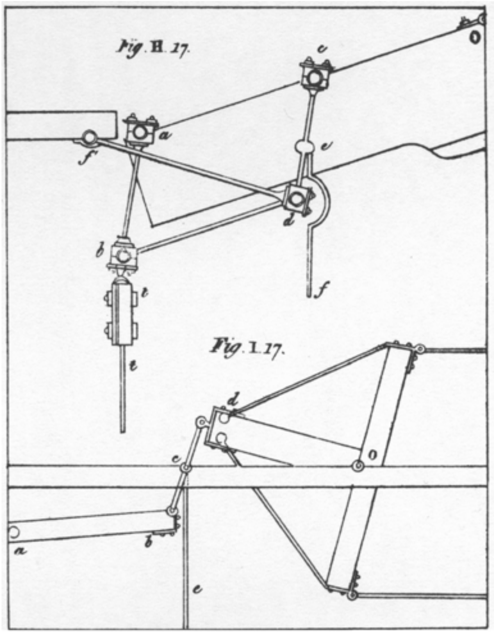

Fig. 2. Watt's straight-line linkages: (Lanz 1808) (Fig. H 17) Watt's extended linkage. (Fig. I 17) Watt's singular linkage, attributed in the Essai to Betancourt.

ing (Figure 2) as it is none other than Watt's straight-line linkage applied to the steam engine. In the book it is attributed to Betancourt. Since the authors always made reference to the known designers of the mechanism, it is quite possible that Betancourt did not know of Watt's design and arrived at the same conclusion through the parallelogram mechanism applied to the steam engine.

In some mechanisms the explanation is very long. For example in the one that talks about the diverse hydraulic wheels using bowls or buckets, or also on the different solutions to the escapement mechanisms used in clockmaking and in part dedicated to mechanisms for plotting curves.

In certain cases, the description of the operation of the mechanism comes accompanied by the explanation of a method for its dimensioning. It is interesting to point out one referring to the design of a cam and another one,

to the optical telegraph is indicated; in I17 Watt's four-link mechanism appears, attributed to Betancourt.

that we will mention later with greater amplitude, related to the design of a mechanism of rectilinear guidance alternative to Watt's.

Another very interesting aspect of the work is that, in most of the mechanisms, their well-known applications are mentioned. In contrast with the extended vision of which the book professes, fundamental mechanisms applied to civil engineering, it is possible to observe that the more related application is in machine tools which appear nineteen times; followed by clockmaking[9] which appears fifteen times; next, mills and the steam engine, with each appearing ten times; which are followed by drop hammers and other similar machines that appear nine times; drawing tools also appear nine times; textile machinery appears seven times; pumps for water elevation appear six times; lifting and dragging machines appear five times; and, hydraulic wheels and polishing machines, with each appearing three times. Some few common applications stand out, such as for example a machine to fillet fish, a mechanism applied to the optical telegraph, another used in the pedal of a piano or several used in fair attractions. Also the use of measurement and control mechanisms is interesting: balls for opening and closing of valves, an instrument for measuring the speed of a ship, and stress control in transmissions.

From the commentaries included in the book it is possible to deduce that, aside from the machines that could be known by the authors in their trips, many mechanisms are selected after exhaustive bibliographical review. Some famous authors of Theatrum Machinarum and machine collection books are mentioned in the Essai: Besson (ca. 1540–1573), Branca (1571–1645), Leupold (1674–1727), Diderot (1713–1784), Berthelot and Belidor (1693–1761). The more referenced sources are diverse collections of inventions and patents published throughout the XVIII century: The "Machines approuvées par l'Académie", the "Annales des arts et manufactures" by O'Reylli and "The repertory of arts and manufactures". Along with them, reports and books by well-known authors such as Daniel Bernouilli, Pitot, Euler, Hut, Coulomb, De la Hire, Hachette and Prony appear.

The importance of this book and its diffusion throughout the first half of the XIX century is authenticated by its numerous editions: three in French in the years of 1808, 1819 and 1840; two in English with the title "Analytical essay on the construction of machines" in the years 1820 and 1822; one in German with the title "Versuch über Zusammensetzung der Maschinen von Lanz und Betancourt" in 1829. Surprisingly there was no edition in Spanish.

[9] Possibly it was due to the great friendship and collaboration with L. Breguet.

In 1875, Reuleaux, talking about the Lanz and Betancourt book, writes: “Without great changes, it has remained of general use until our times and, therefore, it has obtained the approval of general recognition”.[10]

The “Mémoire sur une machine à vapeur à double effet”

At this point, Betancourt’s prominence returns. Betancourt’s description of how he arrived at the knowledge of Watt’s machine is very interesting:

> Being in charge of gathering a collection of models relative to hydraulics as ordered by the Spanish Court, I wished to see a steam engine that had all the discoveries made until the moment. So I arranged to move to England with the purpose of acquiring all the necessary knowledge on the perfection of this machine; I did not ignore that in this country, in which most of the applications of the steam engines have been made, is where greater number of opportunities you can have to recognize the defects and therefore the corrections to apply.
>
> Hardly had I arrived at London, I spoke to several mechanics and physicists; all they had done was to explain to me the effect of steam in the old machines; and they did not say anything to me that was not already known in France. But knowing that the gentlemen Wast and Bolton (*sic*) had made recent discoveries on the steam engine, by means of which they produced the same effects with less combustible, I made the decision to go to Birmingham to meet these famous artists. When I met them they received me with the greatest honesty and as a sign of esteem they showed me their button and silver-clad factories; but they did not show me any of their steam engines, all they did was to tell me, that those they manufactured at that moment were superior to any, because their velocities were controlled voluntarily and they consumed much less combustible than those that they had manufactured previously; they did not let me suspect where did so great advantages came from.
>
> Back to London, a friend got me a permission to see the mills that have been constructed near the bridge of Blas-Friars; they should have three steam engines and each one should drive ten mills. Only one of these machines was mounted, the other two should be mounted imminently.

[10] Reuleaux (1875), p. 13.

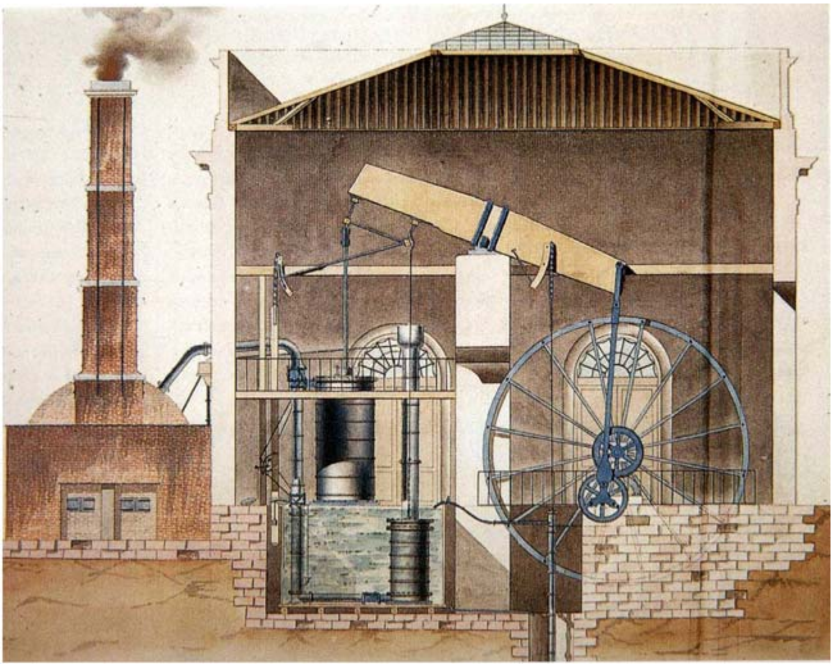

Fig. 3. Watt's Double Acting Steam Engine: Drawing by Agustín de Betancourt (1788). The drawing shows the novel aspects of the machine, some of which were seen and others guessed by him.

At first I was surprised when I saw that the chain joined to the rocker beam and from which the piston within the steam cylinder was suspended had been eliminated; it had been replaced by a parallelogram, of which I will give the description later on (...).

The day after which I saw this machine I started off for France; back in my house I dedicated myself with enthusiasm, remembering faithfully all the pieces that I had been able to see, trying to guess its use; for it I drew diverse diagrams and plots, and got to compose a double acting machine; from that very moment I undertook the construction of the model that has been a success beyond my hopes.

As this machine can be of a great usefulness in the mechanical arts and I have taken advantage of its economy of construction and combustible consumption, I have thought that the Academy would receive with pleasure the description that I am going to give. (Figure 3)

Betancourt presents the "Mémoire sur une machine à vapeur à double effet" the 15th of December of 1789 and signed as "Le chevalier de Betancourt Capitaine au service d'Espagne". The registry of sessions of the 16th of December of 1789 of the Royal Academy of Sciences, states that "Mr. Betancourt has presented a Report on a double acting steam engine" and that commissioners Jean Charles Hut (1733–1799) and Gaspard Monge (1746–1818) have been designated to inform on this Report. In the session of the 10th of February of 1790 the commissioners's report concludes in the following way:

> We thought that the Academy must welcome the fervour and the intelligence of Mr. Betancourt who has brought France the power of a discovery whose knowledge would not have arrived to him in natural form until much later and the report he presents, worthy of approval, must be printed in the collection of those of foreign wise people.

Simultaneously, in 1790, the industrialist Périer, Betancourt's friend, who had asked for and obtained the privilege to install grain mills in the Parisian region, introduced the first double-acting steam engines installed in France in the mill located in l'Île des Cygnes, following Betancourt's instructions.

These facts, related by the same Betancourt, have been cited as an example of industrial spying without enhancing the true prominence of Betancourt. Certainly his role in the diffusion of the double effect steam engine goes beyond the fact of transmitting the data obtained in England.

In the first place, it is a fact that Betancourt could not observe with enough detail all of the machine. In fact, he did not get to have knowledge of a very important element for the controlled operation of the machine, the Watt's flyball governor.

Some historians have wanted to see in Betancourt a good mechanic and a good observer, mere transmitter of which he could see in Albion Mills. Nevertheless, it seems that these qualities are not enough for the development of the machine proposed by Betancourt.

In fact, in 1787, Albion Mills received the visit of three illustrious French visitors. One of them, the famous Coulomb, was an expert on the simple acting steam engine, as he had been a member of four commissions designated in 1783 by the Academy of Sciences to inspect Périer's designs obtained from those of Watt. In his visit to Albion Mills it is a fact that he could see together with his colleagues the machine of double effect and that he even tried to make a sketch of it, when they were caught by an employee and, as a consequence, Boulton was against a later visit to the facilities of Soho. Despite

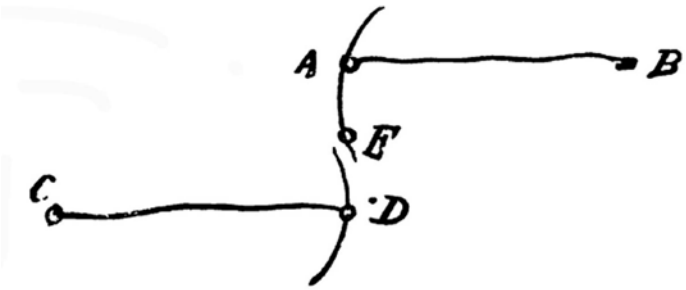

Fig. 4. Drawing by Watt of Watt's singular mechanism: This drawing accompanies Watt's explanation about the justification of the cause by which the singular mechanism of Watt generates an almost rectilinear trajectory.

having seen the machine in detail, until the point of trying to make a sketch, the information did not serve Coulomb to make any proposal of designs after his return to France.[11]

Gaspard F.C.M.R. de Prony (1755–1839), in his "Nouvelle Architecture Hydraulique" (Paris, 1796), makes reference to Betancourt's discovery and, in words that might have been transmitted directly to him by the same Betancourt, makes the following point:

> Artists must know that these observations are difficult to do, when only some few moments have been available to examine a machine masked by the building distributions, that isolate the different parts, even the outer ones, and prevent to have the matching, the set and the general effect.

In order to confirm that Betancourt, in addition to mechanical vision, had a high capacity of innovation when facing the problems of the design of mechanisms, we want to focus our view on a point that has been unnoticed to historians: without anybody revealing it to him, it was Betancourt himself who, when seeing the mechanism of connection of the piston with the rocker arm, deduced that the machine had a double effect. It is indeed at this moment when, in our opinion, an innovating contribution will take place.

Reuleaux, in the introduction to his "Theoretische Kinematik", makes the following comments about the development of the mechanism of rectilinear guidance made by Watt (Figure 4):

[11] Gouzévitch and Gouzévitch (2005), p. 21.

> Watt has shown to us in a letter some indications of the line of thought that led him directly to the alluded mechanism. 'The idea – he writes to his son in November of 1808 – was originated in the following way. Finding the double chains very inconvenient, or the racks and indented sectors for the transmission of the motion from the axis to the piston to the angular motion of the rocker arm, I worked to prove if I would be able to find some means to make the same by means of rotations around centers, and after some time it came up to me that being AB and CD two equal radios rotating around centers B and C, and connected among them by means of a rod AD, moving throughout arcs of equal length, the deviation of the straight line would be approximately equal and opposite, and the point E should describe approximately one straight line, and that if by convenience the radius CD was only half of AB, moving the closest point E to D it would occur the same, and from this construction it was derived the later denominated parallel motion'.
>
> Being interested in the content of this letter, a more meticulous examination of it reveals a deficiency that he might also have discovered. We found in it both the reasons and some of the final results of the exercise of Watt, but we do not obtain indications of any methodical sequence of ideas directed to this aim.

Reuleaux himself affirms that this letter was written by Watt twenty-four years after the invention, with a prolonged time for reflection.

In 1788 – four years after the presentation of the patent of Watt and twenty years before the letter above commented – in the Report on the Steam Engine Betancourt faces and works out the problem of dimensioning the four-bar mechanism. The first theoretical study of Watt's mechanism, that tried to determine the deviation with respect to the rectilinear trajectory, is the one carried out by Prony in the second volume of his "Architecture Hydraulique", published in 1796.[12] Nevertheless, we can affirm that it was Betancourt, in the Report on the Steam Engine presented in 1789, who made the first theoretical study of such mechanism.

In the first place he describes the problem that he tries to solve with the mechanism (Figure 5), in this detail of Betancourt's drawing, some of the parts to which he makes reference to explain the operation of Watt's singular mechanism can be observed: P' and Q' are the ends of the rocker arm; R' and

[12] Prony (1796), seconde partie, pp. 123–142.

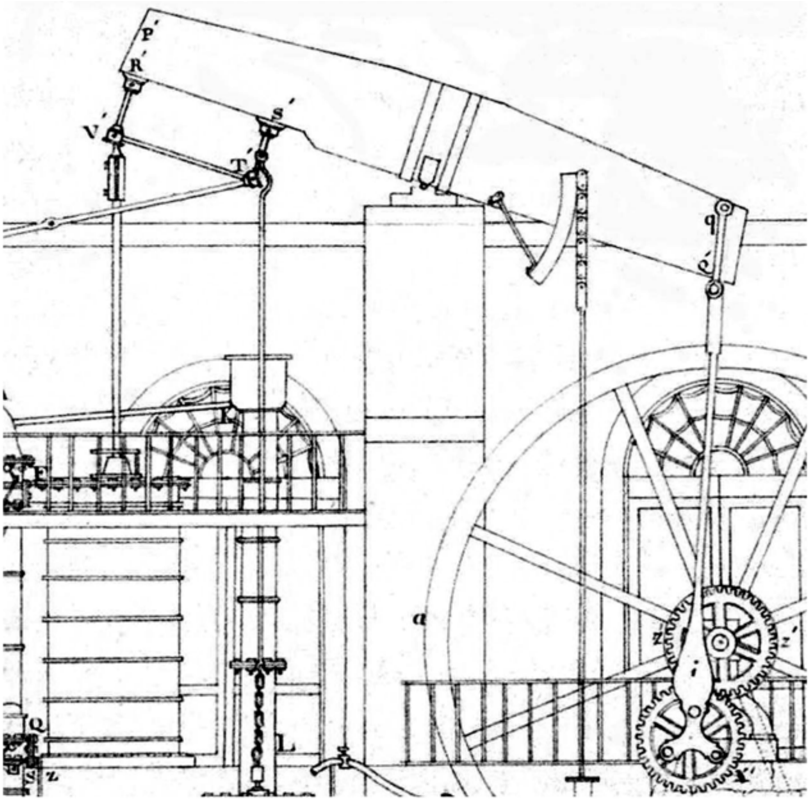

Fig. 5. Watt's double acting Steam engine: Betancourt (1789), illustration III.

S′ are the hinged connection of Watt's mechanism to the rocker arm; T′ is the hinged joint with the lower rocker arm; V′ is the hinged joint of Watt's mechanism to the axis of the piston, being the point that describes an almost rectilinear trajectory.

> We have seen that the piston WW that makes the rocker arm move, is pushed not only from top to bottom but also from bottom to top. In order to produce the first motion, it will be enough to suspend the piston from the rocker arm P′Q′ by means of a chain, as it is done in the common pumps, but is not the same for the motion from bottom to top, because the chain, folding itself, will not be able to communicate the motion to the rocker arm.

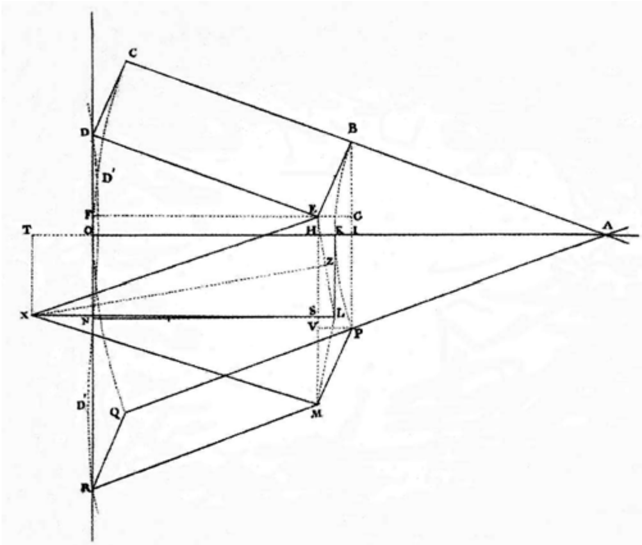

Fig. 6. Geometrical Scheme used by Betancourt to describe the operation of Watt's mechanism: Betancourt (1789), illustration IV.

> It is then necessary to find, in order to communicate to the rocker arm the double motion of the piston, means which are able to produce both effects, without moving sensibly the piston out of the vertical, since the end of the rocker arm travel a circle arc.
>
> This is what Watt has achieved by means of a parallelogram that I think it is of his invention and whose three vertices R′S′T′ have the property to travel circular arcs, whereas the fourth V′, together with the piston, describes a straight line approximately as we have seen it.

Next he set what he denotes as a general problem (Figure 6). In this figure to the upper rocker arm corresponds the segment AC, that rotates around the fixed point A; to the lower rocker arm corresponds the segment XE, that rotates around the fixed point X; to the pantograph would correspond the segments DE, EB, BC and CD, hinged in their four vertices; point D is the one that moves throughout the almost rectilinear trajectory and would be the joint point of Watt's mechanism to the axis of the piston. The drawing represents the mechanism in three positions: the upper rocker arm in the more elevated position (position AC); in the intermediate position (position AO); and in the lower position (position AQ):

> If it is wanted to deal with the problem of a parallelogram with all possible generality, trying to find all the possible solutions, the task could be presented to the geometricians enunciating the case in the following way:
>
> If in a parallelogram CB, DE the points CB draw up circle arcs of radio AC, AB and point E also draws up a circle arc of radio XE, what relation must exist between CB, BE, XE and XT so that the line drawn up by point D approximates most possible to straight line DO perpendicular to AO′

In contrast to the empirical approach of Watt, Betancourt sets out and solves the problem by means of geometrical methods, intuiting that the solution can only be approximated. That is something that will be enunciated by Hachette some years later.[13] At the sight of the complexity of the problem, Betancourt states what he denotes as the particular approach of the general problem:

> Since the only thing which interests to us in this matter is its application to the motion of the steam engine, we will limit ourselves to considering a particular case of the general statement that we have just presented.
>
> We have supposed that the sides of the parallelogram are given and are constant, that point D is on the line DR, perpendicular to AO, in three positions AC, AO and AQ and that angle CÂO is equal to OÂQ. We try to calculate the radius of the circle that goes through the three points ELM.

A clearer description of the procedure will be published later in the Essai. Therefore, Betancourt sets out and solves an example of what, many years later, will be known as the problem of path-generation Synthesis with three precision points.

In a clearer form, Lanz and Betancourt explain in the Essai this method of the so-called Evans' mechanism. A question, without answer at this time, is how this mechanism, attributed to Oliver Evans (1755–1819) and referenced in 1813, appears in the Essai in 1808 accompanied by a method for dimensioning it and without mentioning the sources from where it was taken.

[13] In "Histoire des machines à vapeur depuis leur origine jusqu'à nos jours" by Hachette (1830), he affirms without any proof that the curve described by the connection point of the axis of the piston and Watt's parallelogram is of sixth degree.

Following the description of the procedure to determine the dimensions of this mechanism that appears in the Essai, it can be notice that the method proposed is absolutely the same one that is used in the present texts of Synthesis of trajectory generation with three precision points in a four-bar mechanism.[14] In addition, it is added that this method can be used in Watt's parallelogram mechanism and in the one "solved" by Betancourt. The meaning in this text of the word "solved" is an unknown, but it is clearly about the four-bar singular mechanism patented by Watt. It is possible that, even if Betancourt had already known Watt's extended mechanism, he might have not known the singular mechanism and, therefore, it could have been rediscovered by Betancourt after Watt.

On the Circulation of Works

The Classification of Mechanisms

Although there is not much news on the influence of the Essai in later works, its successive printing in French in 1819 and 1840, in English in 1820 and German in 1829 gives an idea of the importance of the treatise.

Throughout the XIX century other contributions were made to the classifying criteria. In 1811, Borgnis, in his "Traité complet de mécanique", divides the machines in six types: receivers, connecting, modifiers, supports, regulators and operators.[15] As we can observe, it is a classifying criterion that gives more emphasis to the type of function done in the machine than to its kinematic characteristics. In 1830, Ampère, in his "Essai sur la philosophie des Sciences", classifies Monge's studies as a third order science and affirms that:

> This science must, therefore, define a machine, not as it is usually done, as a tool thanks to which the direction and intensity of a given

[14] In figure O17 in the Essai and in the text that accompanies it, the procedure for obtaining a synthesis of rectilinear guidance with three precision points is explained, in a way similar to the one used in a modern manual as, for example, Nieto (1978), pp. 102–103.

[15] According to Borgnis, the receivers are the organs of the machine destined to receive the immediate action of the motors; the connecting are those destined to transmit the movement; the modifiers are those that modify the speed of the diverse mobile bars; the supports are the centers of suspension, rotation or support of other organs; the regulators are those that correct the irregularities of the motion; and the operators are those that produce the final effect.

> force can be altered, but as a tool by which the direction and speed of a given motion can be altered.

With it Ampère confers, on Monge's approach, a category of specific science for the kinematic study of machines. The Essai by Lanz and Betancourt is based on this approach.

Willis, in 1841, introduces in his book "Principles of Mechanisms", a totally new system of classification: instead of using the relation between the absolute input and output motions of the mechanism as classifying criterion, he uses the relative motions between the diverse elements, taking into account the change of direction and speed of the relative motion and whether this relation is constant or variable. He considers that Ampère's definition is in opposition to some of the examples included in the Essai, such as hydraulic wheels and wind-operated mills. Willis only considers mechanisms that are compounded exclusively of solid bodies. Reuleaux affirms that this criterion introduced by Willis was not successful even in England, so that, in general, it was preferred to continue using the Lanz and Betancourt criterion.

Laboulaye, in his "Cinématique" in 1849, rejects Willis's system, and divides the elements of the machines in three types: lever system, winch system and plane system, to which any mobile body belongs depending on whether it has one, two or three fixed points respectively. Nevertheless his approach, based on the motion of points, is not applicable to the motion of bodies.

Morin, in his book "Notions géométriques sur les mouvements", in 1851, and Weisbach, in his paper "Abänderung der Bewegung" (Alteration of the motion), in 1841, remained faithful to Lanz and Betancourt's system. Redtenbacher, Reuleaux's teacher, in "Die Bewegungsmechanismen", printed in 1857, describes and analyzes theoretically the collection of mechanisms in Karlsruhe, and he classifies them by their use, without using any kinematic criterion. Reuleaux himself will describe the approach as nihilistic.

In France, geometrical methods were developed to study the motion of rigid bodies. Example are in Poinsot's book "Théorie de la rotation des corps", which was followed by others, such as the "Eléments de géométrie applique à la transformation du movement" by Girault, in 1858; the "Cinématique" by Belanger, in 1864, and "Traité des mécanismes" by Haton, in the same year. Despite the different approach with respect to the Essai, Girault and Belanger follow the classifying criterion of the transformation of motion. Haton establishes nine categories: rollers, slides, eccentrics, gears, bars and cables, and he groups the last three under the denomination of accessory elements.

Through this development we can observe an insuperable separation between what we could denominate Theoretical Kinematics, of which several of the previously mentioned designers are examples, and Applied Kinematics, in which the approach of the Essai would not be surpassed until 1875. Reuleaux was wondering where the insufficiency of the methods developed until that moment so that in fact Monge's classification developed in Lanz and Betancourt's book was not surpassed. He responds by affirming that the insufficiency of such classification and the later contributions comes from the fact of using the transformation of motions as classifying criterion, without inquiring into the reason for such transformations. Reuleaux discovers that the fundamental reason for the transformation of motion lies on the constraints imposed by the kinematic pairs on the different types of joints between solids. This is the starting point for new classifying approaches.

It is possible to state that the Essai constitutes a first contribution to what would be later called Synthesis of Type. The approach started by this book, and continued by Reuleaux, reached its height in Artobolevsky (1976) that contains more than 5,000 mechanisms, classified by structural and application criteria.

The Rectilinear Guidance

Throughout the XIX century, enormous interest was raised on the part of engineers and mathematicians, to study the properties of the trajectories drawn up by the points of the coupler of a four-bar mechanism. The interest began to appear in France and later it transferred to England and Germany.

As we have already mentioned previously, in 1796, Prony printed the second volume of his "Architecture Hydraulique" and in it he developed the first study on the deviation of the trajectory of Watt's mechanism with respect to the straight line.

Hachette, in his "Histoire des machines à vapeur depuis leur origine jusqu'à nos jours" (1830), includes a proof of equivalence between Watt's mechanism and that developed by Oliver Evans in his Columbia machine before 1813. In 1836, Alexandre Joseph Hidulphe Vincent (1779–1868) published for the first time the equation of the curve of the point that generates trajectories that are almost rectilinear.

Simultaneously, the great Russian mathematician Pafnuti Chebyshev (1821–1894) tried to look for better solutions for the approximate drawing of

rectilinear trajectories and showed his pessimism with respect to the possibility of finding a four-bar mechanism that could draw up precisely a straight line.

It seems that Vincent's work had influence on Charles Nicolas Peaucellier (1832–1913) who, in 1864, was the first to obtain a four-bar mechanism that drew up precisely a rectilinear trajectory.

Many have been the mechanisms developed after Watt's with the purpose of drawing up trajectories that are almost rectilinear. Some of them can be observed in Artobolevsky (1976).

A group of English mathematicians were affected by this interest in mechanisms and, particularly, in the trajectories drawn up by some of its creators, who were precisely the ones that made important contributions to theoretical kinematics: Arthur Cayley (1821–1895), Harry Hart (1848–?), Alfred Bay Kempe (1849–1922), Samuel Roberts (1827–1913) and James Joseph Sylvester (1814–1897).

Roberts and Cayley's works are connected more directly with developments in analytical geometry, mainly in the theory of algebraic curves. Roberts justifies his interest in mechanisms with the purpose of being able to draw up and study the properties of the; he states that the motion of a point of the coupler of a four-bar mechanism describes a curve of sixth degree and that there are three different four-bar mechanisms whose coupler generates the same trajectory. Sylvester and Kempe's works, more elementary, are connected clearly with the possibility of inventing new instruments. Their work reflects in a more evident way that mechanical engineering was, at that moment, one of the dominant technologies.

Beyond the mechanisms that draw up rectilinear trajectories in an exact or approximate form and the properties of the trajectories, a problem remained unsolved and it was guessed by Betancourt and it would be approached in a rigorous form one hundred years after the presentation of the Report on the steam engine: the obtaining of the dimensions of a mechanism that allows a certain trajectory to be generated. Burmester published his "Lehrbuch der Kinematik" (1888) where he sets out for the first time geometrical methods for the solution of the problem of path-generation synthesis.

Modern Interpretation of Main contributions to Mechanism Design

Classification of Mechanisms and Structural Synthesis

The collection and classification of mechanisms is still an important tool that helps design since it facilitates the search of mechanisms that fit the application you are trying to develop. The introduction of concepts such as kinematic pair, link and its different types, has allowed the handling of the classification of mechanisms under new approaches. Classification is not limited to motion transformation criteria, but also takes into account another important element: the structure of the mechanism, understanding as such the definition of the number of kinematic pairs, links, its types and the way in which they are interconnected. Another important classifying element appears associated to the structure, which is the number of degrees of freedom of the mechanism.

The best collection and classification of mechanisms can be found in Artobolevsky's work. Throughout its five volumes (Artobolevsky, 1975), some four thousand mechanisms have been gathered and classified by their structural and functional characteristics. The first and second volumes are devoted to the n-link mechanisms. The third volume is devoted to gear, cam and friction mechanisms. The fourth and fifth volumes are devoted to mechanisms with flexible links and to hydraulic, pneumatic and electrical mechanisms.

Beyond the collection and classification of mechanisms, the study of their kinematic structure has given rise to an important research field within the Machines and Mechanisms Science, which is structural kinematics. Different problems have been approached in kinematic chains and mechanisms: structural synthesis, the problem of isomorphism, structural analysis, the automatic development of mechanisms and the application of structural synthesis to creative design. For them, tools such as the Franke's notation, graph theory and group theory have been used.

There have been important contributions to this field in the 1960s and 1970s from authors such as Crossley, Freudenstein, Hain and Manolescu. In recent years outstanding work has been done in the field of isomorphism detection by authors such as Agrawal and Rao, and in the field of analysis aided by the computer about the structure of kinematic chains by Mruthyunjaya. Diverse works give a vision of the state-of-the-art and the latest contributions in this field (Mruthyunjaya, 2003; Kota, 1993). The research that is carried out in this field makes available to the machine designer computational tools

that facilitate the generation of alternatives in an automatic way so that they fulfil the design criteria given.

Path Generation Synthesis

Path generation synthesis, as part of mechanism dimensional synthesis, has had an important development throughout the second half of twentieth century and continues in the twenty-first century.

The first methods of synthesis exploit the concept of precision points to obtain mechanisms whose trajectory goes exactly through a set of specified points. The problems that were encountered and solved had to do fundamentally with the development and solution of equations that include the condition of going through the precision points and with the problems associated with optimal spacing between the points in order to minimize error. Throughout the 1950s and 1960s, there have been important contributions from authors such as Freudenstein, Suh, Sandor, Roth, Gupta and others.

Due to limitations in the number of precision points, the importance of the application of optimization methods, whose objective is minimizing an objective function with or without constraints, has been greater and greater. In the case of the path generation synthesis, the objective function to minimize can be the error calculated as the difference between the desired trajectory and the generated trajectory. Diverse approaches have been used to solve the problem. A summary of contributions can be found (Angeles, 1993), where different families of methods appear: using least-square normality condition and Lagrange multipliers, general unconstrained optimization, constrained optimization using penalty functions, constrained optimization using general nonlinear programming techniques, mini-max optimization, methods based on probability and statistics. Recent developments include the use of genetic algorithms that try to avoid the problems associated with the selection of the initial solution and its consequences on convergence.

Another completely different approach is based on the use of the storage of coupler curves in a computer database for their comparison with the shape of the curves. To counter the problems generated by the slowness and the possible lack of convergence of optimization methods, other methods that use neural networks have appeared to try to take advantage of the previous knowledge available concerning the problem and its possible solutions.

Structural synthesis and path generation synthesis, to which Betancourt contributed so much to their origin, are still research fields of high interest as

evidenced by the quality of MMS researchers that have devoted their efforts to these fields and by their practical importance to machine design.

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